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We show that direct dark matter detection experiments can distinguish between pointlike and non-pointlike dark-matter candidates. The shape of the nuclear recoil energy spectrum from pointlike dark-matter particles, *e. g.*, neutralinos, is determined by the velocity distribution of dark matter in the galactic halo and by nuclear form factors. In contrast, typical cross sections of non-pointlike dark matter, for example, Q-balls, have a new form factor, which decreases rapidly with recoil energy. Therefore, a signal from non-pointlike dark matter is expected to peak near the experimental recoil energy threshold and to fall-off rapidly at larger energies. Although the width of the signal is practically independent of the dark matter velocity dispersion, its height is expected to exhibit an annual modulation due to the changes in the dark-matter flux. We note that the DAMA data have this spectral property.

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Direct detection of weakly interacting dark-matter particles is the goal of several ongoing and planned experiments, which try to observe the nuclear recoils from interactions with dark matter. In this letter we will show that, in addition to measuring the cross section and the flux of dark-matter particles, the same experiments may be able to probe the structure of dark matter and distinguish between pointlike and extended objects, both of which have been proposed as dark-matter candidates.

A number of reasons have led one to consider pointlike and non-pointlike candidates for dark matter. For example, supersymmetric extensions of the Standard Model predict both the pointlike dark matter in the form of the lightest supersymmetric particles (LSP) [1], as well as a non-pointlike dark matter in the form of SUSY Q-balls [2,3]. The population of LSP could be produced by their freeze-out from equilibrium, while Q-balls could be copiously generated by fragmentation of the Affleck-Dine condensate [3]. Mirror atoms have also been proposed as extended dark matter candidates [4]. Recent analyses of dark matter halos have provided an additional motivation for considering extended objects as dark matter [5]. Numerical simulations with improved resolution seem to predict an excessive number of subhalos and satellite galaxies [6], as well as a cuspy distribution of dark matter, which is at variance with some observations [5]. Self-interacting dark matter [5] could eliminate this apparent discrepancy. However, the required cross section for self-interaction is so large that, for pointlike particles, it violates unitarity, unless they have masses of the order of a few GeV or lighter [7].

This limit does not apply, however, to the extended objects, such as Q-balls, which could be self-interacting dark matter with a wide range of masses $M_{_D}$ and sizes R [8]. Their cross section of self-interaction can be as large as their geometrical size, $\sigma_{_{DD}} \simeq R^2$, and can be in the range necessary for removing the cusp and the galactic satellites [5]:

$$\sigma_{_{DD}} = (0.8 - 10) \times 10^{-24} (M_{_D}/\mathrm{GeV})\mathrm{cm}^2. \qquad (1)$$

Mirror atoms [4] are also not a subject to the unitarity bound.

Various dark matter candidates, pointlike or not, can have interactions with ordinary matter. Although there are several limits on *strong* matter-dark-matter interactions [8], those interactions that do not exceed the strength of standard weak interactions are definitely allowed. Therefore, experiments designed to detect weakly interacting massive particles (WIMP) can detect both pointlike particles and extended objects.

The challenge of identifying the dark matter in the universe requires, in particular, an answer to the question of whether the dark matter particles are pointlike or not. We will show that, for a certain range of masses and sizes of dark-matter particles, this question can be answered based on the shape of the nuclear recoil energy spectrum of the signal in direct detection experiments.

The very nature of extended objects implies that the cross section of their interactions with matter includes a form factor whose dependence on the momentum transfer is an identifiable signature of a non-pointlike object. Although the interaction strength is unknown, if such interactions are detected, the extended objects can be identified by a signal with a recoil energy spectrum strongly peaked at low energies, thus with the largest signal near the experimental threshold and a rapid fall off for larger energies. In fact, the shape of such a signal would be consistent with that reported by DAMA [9].

Although this behavior of the cross section is rather general, we will discuss Q-balls, for definiteness. Let us assume that the dark matter particles are Q-balls, non-topological solitons made of a scalar field ϕ. A Q-ball is a coherent state of Q quanta of the ϕ field. We denote its mass $M_D = M_D(Q)$.

For simplicity, let us assume that the dark matter particles scatter off nuclei via the exchange of some heavy boson Z', the analog of Z exchange in neutralino-nuclear scattering. While the resulting interaction is almost pointlike at some fundamental level, the extended structure of the DM particle causes a form factor F_D to appear in the elastic scattering amplitude. This form factor is analogous to the nuclear form factor $F_N(A)$ that reflects the nuclear structure.

The direct detection strategy for WIMPs relies on detecting the recoil of nuclei with atomic number A and mass $M_N = M_N(A)$. Dark-matter particles have velocities $\beta = v/c \simeq 10^{-3}$, so the maximum energy deposited in a collision is

$$\Delta E = 2\frac{\beta^2\mu^2}{M_N(A)}, \quad (2)$$

where μ is the reduced mass of the dark matter particle, with mass $M_D(Q)$, and the target nucleus, with mass $M_N(A)$. Existing and future detectors, have energy thresholds of a few keV. Hence, we require that $\Delta E \gtrsim 10$ keV. For $M_N(A) \simeq 100$ GeV, this implies $M_D(Q) \gtrsim M_N(A)$. We, therefore, restrict our discussion to Q-balls heavier than nuclei, for which

$$\Delta E \simeq 2\beta^2 M_N(A). \quad (3)$$

The differential cross section for elastic scattering is

$$\frac{d\sigma}{dq^2} = \frac{(G'_F)^2}{4\pi}\frac{M_{Z'}^4}{\left(q^2 - M_{Z'}^2\right)^2}\frac{A^2}{\beta^2}Q^2\,|F_A|^2\,|F_D|^2, \quad (4)$$

where, q is the momentum transfer, G'_F is the analogue of the Fermi constant for Z' exchange, while F_A and F_D are the form factors of the nucleus and the Q-ball, respectively:

$$F_{D,A}(q) = \int d^3\vec{r}\, e^{i\vec{q}\vec{r}}\, \rho_{D,A}(\vec{r}). \quad (5)$$

To a good approximation, the form factor of a nucleus can be calculated using $\rho_A = \rho_0/\left(1 + \exp\{(r-c)/z\}\right)$, where, for example, for Ge, $c = 4.503, z = 0.583$.

If (i) the size of a DM particle exceeds the size of the nucleus, and (ii) the putative interaction with quarks allows a coherent channel, then the form factor F_D imprints the cross section (4) with an easily identifiable signature: a rapid fall-off for large q.

For definiteness we assume that the cross section σ_{DD} and mass M_D satisfy the relation (1), that is

$$R \simeq (1-3)\times 10^{-12}\text{cm}\left(\frac{M_D}{\text{GeV}}\right)^{1/2}. \quad (6)$$

We now demand that the collision be elastic. Q-balls have nearly massless modes, for example, the Goldstone mode of a spontaneously broken U(1) symmetry. The lowest excitation has a Compton wavelength of the order R and energy gap $\simeq 1/R$. The collision is elastic as long as the energy transfer, which is at most $2\beta^2 M_N(A)$, is smaller than $1/R$. Hence, the collision is always elastic for

$$R < \frac{1}{2\beta^2 M_N(A)} \simeq \frac{1}{0.1\text{MeV}} \simeq 0.4\times 10^{-11}\text{cm} \quad (7)$$

Using eq. (6), we get the upper limit on the mass of Q-balls that scatter elastically, $M_D < 10^4$ GeV. As mentioned above, a detection threshold of a few keV requires the Q-ball to have a mass similar or larger than the nucleous mass, which is of the order of 10^2 GeV.

Hence, we restrict our discussion to the range[1]

$$10^2\text{GeV} \lesssim M_D \lesssim 10^4\text{GeV}, \quad (8)$$
$$10^{-11}\text{cm} \lesssim R \lesssim 10^{-10}\text{cm} \quad (9)$$

The form factor F_D in eq. (5) can be evaluated for a given Q-ball profile. Depending on the scalar potential $U(\phi)$, Q-balls can have a thin-wall [10] or a thick-wall profile [11]. However, in either case, for $qR > 1$

$$F(q) \propto \frac{1}{(qR)^n}, \quad n \geq 2. \quad (10)$$

$F(q)$ decreases rapidly for $qR > 1$. The slowest possible fall-off occurs when the Q-ball profile is approximated by a step-function. In this case,

$$F_{\text{step}}(q) \propto \left(\frac{qR\cos(qR) - \sin(qR)}{(qR)^3}\right) \quad (11)$$

which fall off as $(qR)^{-2}$, for $qR > 1$.

For realistic profiles, $F(q)$ need not have the oscillating behavior of eq. (11) and, more importantly, it has a faster asymptotic fall-off, *e. g*, $\sim (qR)^{-3}$ or faster.

The key observation is that, for the range of parameters in eqs. (8-9), $(qR) > 1$ in typical direct detection experiments. Indeed, the maximum momentum transfer in an elastic collision is $q_{max} \simeq 2\beta M_A \simeq 200$ MeV. On the other hand, the minimal observable energy of recoil is determined by the experimental threshold of a few keV.

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[1] In the case of mirror matter, if the Z' is coupled to both the ordinary quarks and the electrons, the ordinary atoms would scatter coherently off a mirror atom. In this case the range of radii for which the scattering is elastic and coherent extends as far as to $10^{-11}\text{cm} \lesssim R \lesssim 10^{-8}$cm.

For $M_D > M_A$, this means $q^2/2M_A > 1$ keV, or $q \gtrsim 10$ MeV. Hence, from eqs. (8-9),

$$5 \lesssim (qR) \lesssim 10^3. \tag{12}$$

The q-dependence of the differential cross section (4) is, therefore, dominated by $|F_D|^2 \sim (qR)^{-2n}$, $n \geq 2$:

$$\frac{d\sigma}{dq^2} \lesssim \frac{1}{(qR)^4} \tag{13}$$

Thus, the nuclear recoil energy spectrum falls off very fast with increasing energy, independently of the incident DM velocity distribution. The signal is dominated by the low-energy events near the threshold. The magnitude of this signal should be modulated by the annual variation of the DM velocity distribution. In contrast, the signal from pointlike dark matter would have a wider recoil-energy profile determined by the velocity distribution of dark matter particles and the nuclear form factor.

The reason why the nuclear F_A form factor does not have a similar effect on the shape of the signal from pointlike dark matter is because the corresponding value of (qR) is smaller. It is essential that a condition $(qR) > 1$ is satisfied for extended objects we are considering.

We note that this spectral feature is consistent with the signal recently reported by the DAMA experiment. Of course, if this signal is interpreted as detection of non-pointlike dark matter, one expects that experiments with lower threshold, for example CDMS, should detect an even stronger signal near their (lower) threshold.

Finally, we show that, for some reasonable model parameters, one can get the detection rates for dark-matter Q-balls as high as those for neutralinos. The cross section in eq. (4) is, of course, model-dependent. The constant $G'_{_F}$ reflects the strength of some interactions beyond the Standard Model. The bounds on new heavy Z' bosons imply that $M(Z') \gtrsim 500$ GeV. Let us take $G'_{_F} \simeq 10^{-4} G_{_F}$, which corresponds to a TeV scale of new physics. The form factor $|F_D|$ can be taken of the order of 10^{-6} for $n = 3$ and $(qR) \simeq 10$, or, equivalently, $n = 2$, $(qR) \simeq 30$. For the cross section to be of the order of weak cross section, the enhancement from coherent scattering Q^2 must compensate for the smaller coupling and the form-factor suppression, that is $10^{-4} \times 10^{-6} \times Q^2 \simeq 1$. This is possible for $Q \simeq 10^5$, which is within the range of values considered in Ref. [8]. Using the parameterization from Ref. [8], Q-ball with mass $M_{_D} \simeq \mu Q \simeq 10^4$ GeV and radius $R_{_Q} \simeq \mu^{-1} Q^{1/3} \simeq 10^{-10}$cm is within the range of eqs. (8-9) for $Q \simeq 10^5$, $\mu \simeq 0.1$ GeV.

To conclude, direct detection experiments designed to search for weakly interacting massive particles may be able to discern the spatial extent of a dark-matter particle in a certain range of parameters. The signal from extended objects would pile up near the experimental threshold, unlike a typical signal from a pointlike dark matter. This offers an exciting possibility to discover and distinguish a pointlike candidate from an extended object.

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